DESIGN OF A TETHER BOOST FACILITY FOR THE HUMAN MARS MISSION

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Abstract

We have developed a preliminary architecture for a tether boost facility designed to handle cargo payloads for the Human Mars Mission. This facility will impart a total ΔV of 2.5 km/s to the payloads, boosting them from LEO holding orbits to high-energy elliptical orbits in preparation for Trans-Mars-Injection rocket burns. Our analyses indicate that the total system mass required, using currently available tether materials and reasonable safety factors, would be approximately 4.6 times the payload mass, or 391 mt of facility mass for a 85 mt payload. Economically, this system would compare very favorably to a SEP boost stage if it is used for repeated missions. The system would provide rapid transfer times, comparable to chemical rocket transfer times, yet require no propellant resupply. The system could also provide direct Mars transfer insertion for 15 mt payloads, and handle significant traffic to GEO and the Moon.

Introduction

NASA is currently developing preliminary designs for the first Human Mars Mission, targeted for flights during the 2011 and 2013/2014 Mars transfer opportunities.[1] For mankind to be able to afford a sustained human presence on Mars beyond this first visit, the cost of frequent transportation to and from Mars must be reduced by an order of magnitude. A significant portion of the cost reduction must come from minimization of expendables and the amount of propellant that must be launched into Earth orbit.

Tether systems can provide the fully-reusable propellantless in-space propulsion capability needed to achieve the cost reductions for frequent travel to Mars. In this paper, we will develop and analyze a design for a tether system capable of providing 2.5 km/s of the 3.8 km/s total ΔV needed to inject payloads in LEO into a 178 day Mars transfer. We will then compare this system to solar-electric propulsion (SEP) upper stages currently being considered for this part of the mission.

The Mission:

In order to facilitate an apples-to-apples comparison, we will design the tether system to accomplish the same mission as the SEP stage in the baseline Human Mars Mission design. The SEP stage would boost cargo payloads massing approximately 85 mt from low-LEO orbits to an 800 x 67,000 km High Elliptical Orbit (HEO). From this orbit, the cargo vehicles would perform a ~1.3 km/s Trans-Mars Injection (TMI) maneuver.

Elliptical-Orbit HEFT System

For this system, we will use the High-Strength Electrodynamic Force Tether (HEFT) Facility concept, which combines rotating momentum-exchange tether principles with electrodynamic tether propulsion to provide a means for repeatedly boosting payloads from LEO to higher orbits or interplanetary trajectories without requiring propellant expenditure.[2] The HEFT facility would consist of a central station with a power supply, a long, tapered, high-strength tether, and a grapple vehicle at the end of the tether. The tether would have a conducting core so that current can be driven along the tether by the station's power supply. The HEFT facility would be placed in an elliptical orbit with a perigee in LEO, and its rotation would be chosen so that the grapple vehicle at the tether tip could rendezvous with payloads in low-LEO orbits when the tether is at the bottom of its rotation. After picking up a payload, the tether facility would carry the payload for one orbit and, on its return to perigee, release the payload at the top of its rotation,

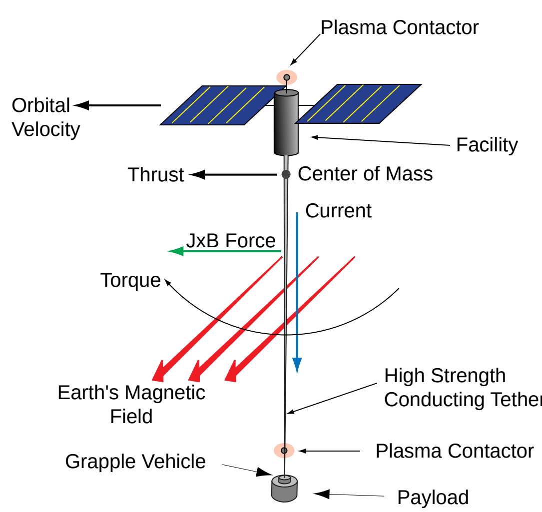

Figure 1. Schematic of the HEFT Facility concept.

injecting the payload into a high elliptical orbit. In this design, the total ΔV the HEFT facility imparts to the payload is 2.5 km/s. In boosting the payload's orbit, the facility will have imparted some of its orbital momentum and energy to the payload, reducing its own apogee. The HEFT facility will then use its power supply to drive current through the tether when it is near perigee, reboosting its apogee. This will enable it to restore its orbital momentum and energy so that it can boost additional payloads. This combination of momentum-exchange and electrodynamic tether propulsion enables the HEFT system to rapidly boost payloads out of LEO without requiring propellant expenditure.

In order to determine the feasibility and required mass of this system, we must determine the tether length, rotation rate, and orbit characteristics that will permit the tether to rendezvous with the payload and throw it into the desired high energy orbit.

In this analysis, the payload of mass M_P begins in a circular orbit with radius r_{IPO}. The payload orbits with a velocity of

$$V_{p,0} = \sqrt{\frac{\mu_e}{r_{IPO}}}. \tag{1}$$

The facility is placed into an elliptical orbit with a perigee above the payload's orbit, with the difference between the facility's initial perigee and the payload orbital radius equal to the distance from the tether tip to the center of mass of the facility and tether:

$$r_{p,0} = r_{IP0} + (L - l_{cm,unloaded}), \tag{2}$$

where L is the tether's total length, and $l_{cm,unloaded}$ is the distance from the facility to the center of mass of the system before the payload arrives (this distance must be calculated numerically for a tapered tether).

The initial tether tip velocity is equal to the difference between the payload velocity and the perigee velocity of the tether facility's center-of-mass:

$$V_{t,0} = V_{p,0} + V_{IP0}. \tag{3}$$

In order to ensure that a payload will not be "lost" if it is not caught by the tether on its first opportunity, we choose the semimajor axis of the facility's orbit such that its orbital period will be some rational multiple N of the payload's orbital period:

$$P_{f,0} = NP_{IPO} \quad \Rightarrow \quad a_{f,0} = N^{2/3}\ r_{IPO} \tag{4}$$

For example, if N=8/3, this condition means that every three orbits the facility will have an opportunity to rendezvous with the payload, because in the time the facility completes three orbits, the payload will have completed exactly eight orbits.

An additional consideration in the design of the system are the masses M_f and M_t of the facility and tether, respectively. A significant facility mass is required to provide "ballast mass." This ballast mass serves as a "battery" for storing the orbital momentum and energy that the tether transfers to and from payloads. If all catch and throw operations are performed at perigee, the momentum exchange results primarily in a drop in the facility's apogee. A certain minimum facility mass is necessary to keep the post catch and throw apogees of the facility orbit above the Earth's upper atmosphere. Most of this "ballast mass" will be provided by the mass of the tether deployer and winch, the facility power supply and power processing hardware, and the mass of the tether itself. If additional mass is required, it could be provided by waste material in LEO, such as spent upper stage rockets and shuttle external tanks.

The tether mass will depend upon the maximum tip velocity and the choices of tether material and design safety factor, as described in Reference 3. For a tapered tether, the tether's center-of-mass will be closer to the facility end of the tether. This can be an important factor when the tether mass is significant compared to the payload and facility masses. In the calculations below, we have used a model of a tether tapered in a stepwise manner to calculate tether masses and the tether center-of-mass numerically.

By conservation of momentum, the perigee velocity of the center of mass of the tether and payload after rendezvous is:

$$V_{p,1} = \frac{V_{p,0}(M_f + M_t) + V_{IPO}M_P}{(M_f + M_t) + M_P}. \tag{5}$$

When the tether catches the payload, the center-of-mass of the tether system shifts downward slightly as the payload mass is added at the bottom of the tether:

$$r_{p,1} = \frac{r_{p,0}(M_f + M_t) + V_{IPO}M_P}{(M_f + M_t) + M_P} \tag{6}$$

In addition, when the tether catches the payload, the angular velocity of the tether does not change, but because the center-of-mass shifts closer to the tip of the tether when the tether catches the payload, the tether tip velocity decreases. The new tether tip velocity can be calculated as

$$V_t^{'} = V_t \frac{\left(L - l_{cm,loaded}\right)}{\left(L - l_{cm,unloaded}\right)} \tag{7}$$

At this point, it is possible to specify the initial payload orbit r_{IPO}, the payload/facility mass ratio χ, the facility/payload period ratio *N*, and the desired final orbit, and derive a system of equations from which one particular tether length and one tether tip velocity can be calculated that determine an "exact" system where the tether tip velocity need not be adjusted to provide the desired C_3 of the payload lunar trajectory. However, the resulting system design is rather restrictive, working optimally for only one particular value of the facility and tether masses, and results in rather short tether lengths that will require very high tip acceleration levels. Fortunately, we can provide an additional flexibility to the system design by allowing the tether facility to adjust the tip velocity slightly by reeling the tether in or out a few percent. If, after catching the payload, the facility reels the tether out by an amount ΔL, the tip velocity will increase due to conservation of angular momentum:

$$V_t^{''} = \frac{V_t^{'}\left(L - l_{cm,loaded}\right)}{\left(L - l_{cm,loaded}\right) + \Delta L} \tag{8}$$

When the facility returns to perigee, it can throw the payload into higher energy orbit with perigee characteristics:

$$r_{p,LTO} = r_{p,1} + \left(L - l_{cm,loaded}\right) \qquad V_{p,LTO} = V_{p,1} + V_t^{''} \tag{9}$$

System Design:

Using the equations above, standard Keplerian orbital equations, and equations describing the shift in the system's center-of-mass as the payload is caught and released, we have calculated a design for a "MarsHEFT" system capable of transferring picking up payloads from a circular LEO orbit and throwing them to a 800 x 67,000 km pre-TMI orbit. The payload and tether orbits are shown to scale in Figure 2.

Payload:

- mass M_p = 85 mt
- altitude h_{IPO} = 545 km
- velocity V_{IPO} = 7.59 km/s

Tether Facility:

- tether length L = 210 km
- tether mass Mt = 221 mt (2.6xM_p) (Spectra 2000 fiber, safety factor of 3)
- station mass M_f = 170 mt ≈ 2 x payload mass
- **total system mass M = 391 mt ≈ 4.6 x payload mass**
- initial tether tip velocity: $V_{t,0}$ = 1507 m/s
- High Energy [Pre-Catch] Orbit:
  - perigee altitude $h_{p,0}$ = 699 km,
  - apogee altitude $h_{a,0}$ = 13170 km
  - eccentricity e_0 = 0.468
  - period P_0 = 8/3 P_{IPO} (rendezvous opportunity every 12.7 hrs)

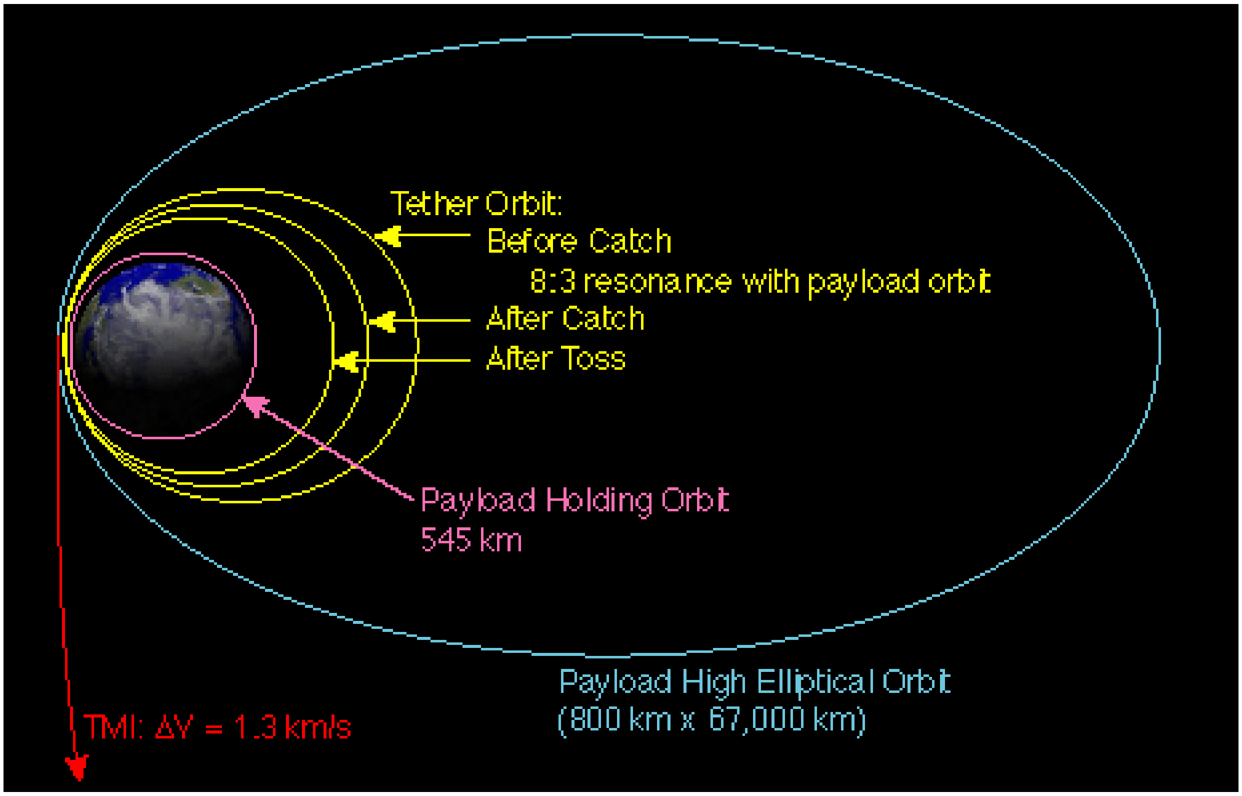

Figure 2. Orbital architecture of the MarsHEFT system.

- rendezvous acceleration g_{tip} = 1.5 gees
- post-catch orbit (COM):
  - perigee altitude $h_{p,0}$ = 671 km,
  - apogee altitude $h_{a,0}$ = 9219 km
  - eccentricity e_0 = 0.377
- After catching payload, facility unreels 0.9 km of tether to absorb capture shock and adjust tip velocity
- Adjusted Post-Catch tip velocity: V_t'' = 1236 m/s
- Post Catch tip acceleration: g'_{tip} = 1.2 gees
- Low Energy [post-throw] orbit:
  - perigee altitude $h_{p,0}$ = 643 km,
  - apogee altitude $h_{a,0}$ = 6375 km
  - eccentricity e_0 = 0.29

<u>High-Energy Payload Orbit:</u>

- perigee altitude $h_{p,lto}$ = 800 km
- apogee altitude $h_{a,lto}$ = 67,000 km
- perigee velocity $V_{p,lto}$ = 10.058 km/s
- orbit energy parameter C_3 =-9.9 km^2/s^2

HEFT System Reboost

After boosting the payload, the HEFT facility will be left in a lower energy elliptical orbit with a semimajor axis that is approximately 3400 km less than its original orbit. It can then use electrodynamic propulsion to reboost its apogee by driving current through the tether when the tether is near perigee. Because the tether is rotating, the direction of the current must be alternated as the tether rotates to produce a net thrust on the facility. Modeling of reboost of HEFT tether systems indicate that the system could reboost its semimajor axis at a rate of 50 km·mt /day·kW. Thus if the 391 mt facility has a 100 kWe power supply, it can reboost its orbit within about 270 days. If, instead, it has the 800 kWe power supply baselined for the Mars mission SEP stage, it could reboost its orbit in about 1 month.

Comparison to SEP Stage

In the SEP/Human Mars Mission scenario, a SEP stage massing 22 mt would use roughly 48 mt of Xenon fuel to boost the 85 mt payload into the 800 x 67,000 km HEO, with a transfer time on the order of one year.[4] Typically, a SEP stage would have a lifetime of two mission, limited by thruster and solar panel degradation. Thus, for this comparison, we will take the required on-orbit mass of a SEP stage to be (2x48 + 22)/2 = 59 mt. If Earth-to-Orbit launch costs are the primary cost driver, the 391 mt tether facility would gain a cost advantage within 7 boost missions. Additional factors, such as the limited world supply and high cost of Xenon, may reduce the number of missions needed for break-even. Use of the tether facility for other missions, as described below, would further improve its economic competitiveness.

Because much of the tether facility mass is simply ballast mass, used as a "battery" to store orbital energy and momentum, the system can utilize spent upper stages, shuttle external tanks, and other on-orbit mass to provide this ballast. Thus it may be possible to significantly reduce the total launch costs for deploying the HEFT tether system.

An additional advantage of the HEFT system is that it provides transfer times comparable to high-thrust chemical rocket systems, without requiring propellant expenditure. This can help to significantly reduce degradation of the Mars cargo systems due to the extended radiation exposure they would experience in a SEP slow-spiral boost scenario, and could reduce the radiation health risks to astronauts when it is eventually used for transporting personnel.

System Use for Direct Mars Injection, GTO Injection, and Lunar Transport

In addition to boosting large Mars-bound payloads into high elliptical orbits in preparation for TMI burns, this HEFT system could also perform numerous other important propulsion missions. With a tether sized to provide the 2.5 km/s ΔV to Mars-bound payloads massing 85 tons, could, by boosting its orbit and increasing its rotation rate, be used to inject 15 mt payloads directly into rapid Mars transfer trajectories. It could also boost 100 mt payloads from 300 km circular holding orbits into GTO trajectories, providing a reusable system for deploying ambitious space solar power stations and other GEO satellites. It could also be used to throw 40 mt payloads into minimum-energy lunar transfer trajectories. Thus, such a system could defray its development and launch costs by handling multiple propulsion missions. Furthermore, these other missions would provide opportunities to validate the HEFT system before it is used for a high-value Mars mission.

Summary

We have developed a preliminary architecture for a HEFT tether facility designed for the Human Mars Mission. This facility would impart a total ΔV of 2.5 km/s to the payloads, boosting them from LEO holding orbits to high-energy elliptical orbits in preparation for TMI rocket burns. Our analyses indicate that the total system mass required, using currently available tether materials and reasonable safety factors, would be approximately 4.6 times the payload mass, or 391 mt of facility mass for a 85 mt payload. Economically, this system would compare very favorably to a SEP boost stage if it is used for repeated missions. The system would provide rapid transfer times, comparable to chemical rocket transfer times, yet require no propellant resupply. The system could also provide direct Mars transfer insertion for 15 mt payloads, and handle significant traffic to GEO and the Moon.

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